



# HYBRID SIMULATION COMBINED WITH FATIGUE TESTING METHOD

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## ABSTRACT

Hybrid simulation technique, also referred as hybrid testing, is an innovative and powerful approach of analyzing an integrated large-scale structural system under dynamic loading conditions. Hybrid simulation combines the lab testing with numerical analysis to explore the benefits of both methodologies. The basic idea is to numerically represent part of the substructures using well-established mathematical models, while physically testing rest of the other substructures that may have complicated or unknown mechanical properties. The coupling between the two substructure sets is achieved by enforcing equilibrium and compatibility at the interface using a transfer system such as servo-hydraulic actuators. In this study, a process was created to combine hybrid simulation and fatigue testing of a wind turbine blade in order to accurately simulate the blade fatigue damage during its entire

service life. The fatigue testing was divided into multiple sections. At beginning of each section, a hybrid test was conducted to calculate the loading command time histories for the subsequent fatigue testing of the physical substructure. The alternation between hybrid simulation and fatigue testing ensured that the property change of the blade during its entire service life was accurately simulated. A small scale test was conducted to validate the process. The full scale blade test will be conducted in the near future.

ANSYS was used to model the numerical part of the blade structure. ANSYS was connected to MTS test system through a unified framework of OpenFresco to perform hybrid simulation. A generic client element was implemented into ANSYS using its published programming interfaces. OpenFresco acted as the middleware to manage the communication between computational elements and MTS testing systems.

*Keywords:* Hybrid simulation, Fatigue testing, ANSYS, OpenFresco

## **1. Introduction to Hybrid Simulation Solution**

Hybrid simulation is an innovative and cost effective way to evaluate structures, where the full structure is divided into physical and numerical substructures. The governing equations of motion are solved by a step-by-step numerical integration process. At each step, the incremental displacement of the structure to a specified loading event is computed based on the current state of the physically and numerically modeled portions of the structure and applied to the physical substructure. The physical substructure of the overall hybrid model can be tested in one or more laboratories using servo hydraulic test equipment. The hybrid simulation method therefore gives the researcher the ability to use lab testing facilities to simulate large specimens with large deformation. The method is more accurate than pure analytical analysis because highly nonlinear and/or numerically difficult to simulate portions are thus physically simulated, and it is more efficient than full structure test because well understood portions can be modeled reliably using finite element models. Another advantage of hybrid simulation is that the loading history is determined during the course of an experiment for a given system subjected to a specific loading event, which makes substructure/component test more accurate [1, 2, 3, 4]. Alternatively, hybrid simulation can also be considered as a conventional finite element analysis where physical models of some portions of the structure are embedded in the numerical model. Due to the advantages of hybrid simulation, more and more researchers have utilized this method in different industries, such as civil/structures, automobile, and wind energy [5, 6, 7, 8].

To accelerate the development and refinement of hybrid simulation techniques, an environment independent software framework, Open Framework for Experimental Setup and Control (OpenFresco), that is robust, transparent, scalable and easily extensible was developed by UC Berkeley [3, 4]. The framework allows domain researchers to carry out hybrid simulations without specialized knowledge about the underlying software. It also

enables hybrid simulation and IT specialists to extend the frontiers of the methodology, by permitting the addition of new control systems, integration methods, communication strategies, and computing resources. Over the years, OpenFresco has gained much popularity. More and more researchers use it as a mid-mare to connect analysis software and test setup in their hybrid simulation work.

Technical University of Denmark (DTU) has attempted to use hybrid simulation to test wind turbine blades. In their work, a hybrid simulation platform capable of performing quasi-static and real-time substructure testing of large composite structures has been developed and demonstrated. An initial hybrid simulation architecture and strategy were presented to form the basis for an upcoming single component hybrid simulation on the SSP34m wind turbine blade. A communication loop capable of accommodating single-component hybrid simulation was developed through the LabVIEW environment. The approach was verified by small scale hybrid tests. Figure 1 shows the DTU blade hybrid simulation setup.

MTS has long been offering the state-of-the-art testing technology, also in collaboration with worldwide leading research institutions, to provide quasi-static, real-time and soft real-time, as well as geographically distributed hybrid simulation solutions. These solutions are tailored to meet the needs of different application purposes, from complicated test setup using multiple control channels with dynamic cross-couplings; to large-scale finite element models with nonlinear geometry and material properties.

The hybrid simulation technique has gained tremendous popularity over the last decade among the structural engineering research community. To this date, MTS has deployed more than one hundred hybrid simulation systems around the world in civil/structure, ground vehicle, and aerospace industries.

DTU and MTS have decided to team up to continue exploring the methodology of conducting hybrid simulation on wind turbine blades. For the purpose of utilizing existing tools, it is decided that OpenFresco will be the hybrid simulation frame work. Since the previous blade analysis work was done by using ANSYS, a connection between ANSYS and OpenFresco needs to be established so that the hybrid simulation can be conducted using ANSYS. The hybrid simulation would generate loading command for the subsequent fatigue test. For this reason, MTS has developed a generic client element in ANSYS handling the communication between ANSYS and OpenFresco. A procedure to conduct hybrid simulation coupled with fatigue tests has been developed and validated by a small scale test at MTS. The full scale blade tests will be conducted in the near future at DTU.

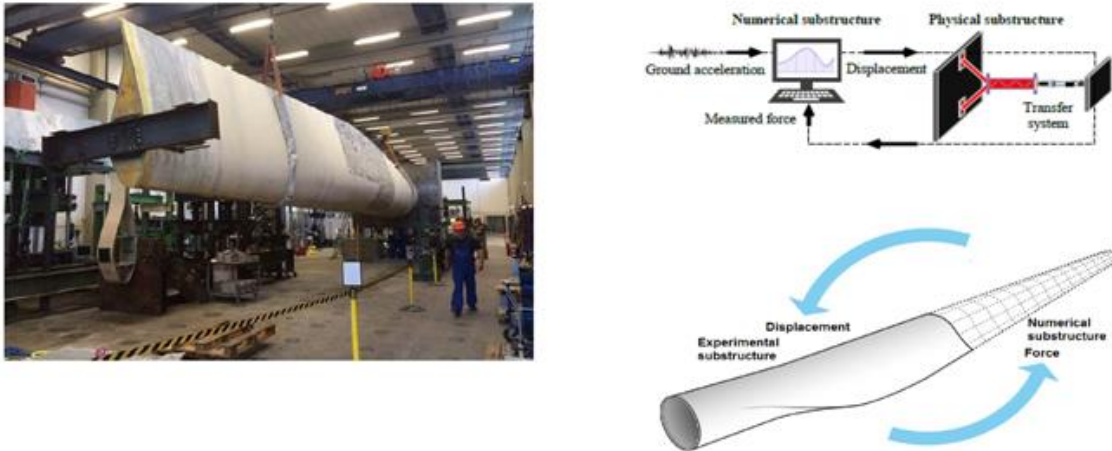


Figure 1, DTU wind turbine blade hybrid test setup

### Hybrid Simulation Framework

OpenFresco framework has ExperimentalElement, ExperimentalSite, ExperimentalSetup and ExperimentalControl classes defining the various operations, data, and relationships needed during a hybrid simulation to provide a bridge between a standard finite element analysis program and laboratory control and data acquisition systems.

OpenFresco is independent of the finite element (FE) software used. However, the software must allow the addition of a new element. This user defined generic client element only needs to be implemented once for a FE package. The new generic client element opens connection, sends and receives data to and from OpenFresco. The generic client elements for Abaqus, LS-Dyna, Matlab, and OpenSees [4, 5] have been created so that hybrid simulation can be conducted with these FE packages connecting to OpenFresco.

MTS Computer Simulation Interface and Configuration (CSIC) software serves as the communication interface between OpenFresco and MTS Flextest controller and execute common structure testing commands and data acquisition operations. The data exchange is performed through the user defined generic client element in the FE package and the existing 793 system software APIs. This interface provides an easy way to map the control points and degrees of freedom in the computer model to the system's actuators and physical control channels. Figure 2 shows the schematic for OpenFresco – CSIC hybrid simulation framework.

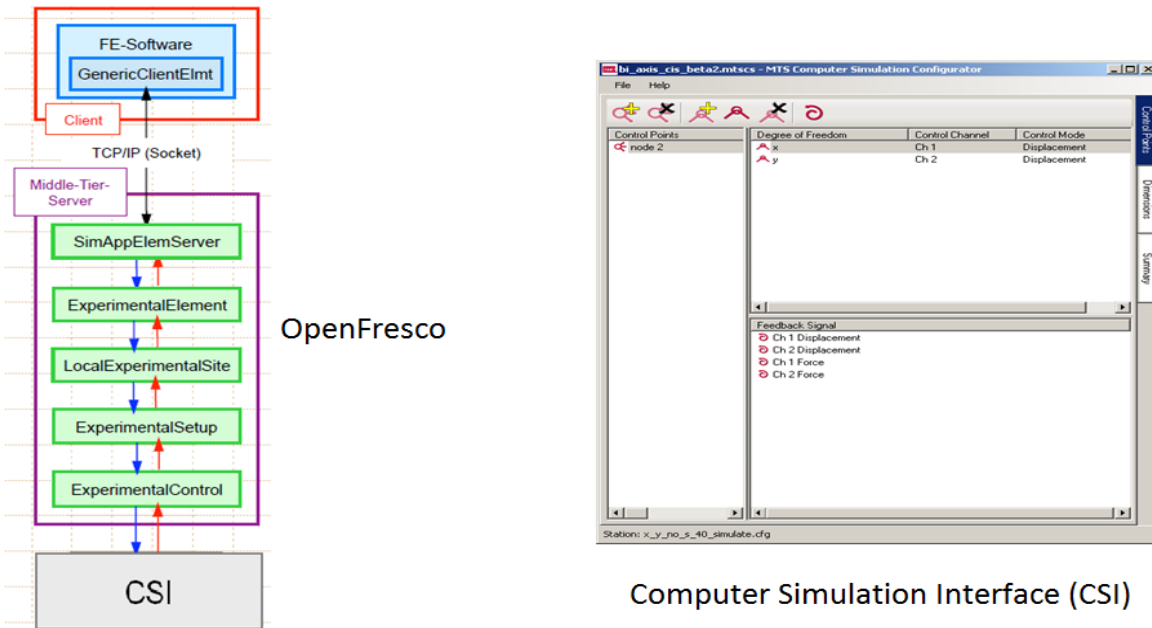


Figure 2, Hybrid simulation with OpenFresco and MTS CSIC schmetic

### ANSYS and OpenFresco connection

ANSYS User-Programmable Features (UPFs) are ANSYS capabilities for which users can write their own FORTRAN routines. As such, UPFs make it possible for users to build customized applications. One type of ANSYS UPFs is the user element routine (UserElem.f), which provides an interface to program user-defined element. With this API, it is possible to create virtually any element type.

A generic client element is implemented using the UserElem API. The element communicates with OpenFresco middle-tier server through a tcp/ip connection. This user element approach allows connected codes to run continuously and concurrently with high computational efficiency. Therefore, it is ideal for hybrid simulation solution.

The user element subroutine needs to be compiled and linked with various ANSYS and Windows libraries. There are multiple methods to compile and link ANSYS UPFs. Among which, the most generalized method recommended by ANSYS is to create a custom ANSYS executable.

### Reduced order model technique in Real-time Hybrid Simulation

In terms of realtime hybrid simulation, the MathWorks xPC target solution is used to integrate the computer model with physical testing. The Matlab/Simulink offers a powerful environment to program user defined functions for advanced control and digital signal processing functionalities. These functions, e.g the outerloop actuator controller/compensator can be compiled into C code, and downloaded and executed on a target real-time kernel xPC. The data transfer between xPC target and MTS realtime servo-

controller uses SCRAMNet reflective memory technique, which introduces ultra-low latency for relatively large data channel counts. Compared to the quasi-static hybrid simulation solution, these upgraded hardware requirements are necessary to fulfill the realtime testing challenges.

Reduced order modelling (ROM) technique is often used in real-time hybrid simulation implementations to achieve guaranteed execution performance, where global structural dynamic response is interested with little or no expected structural nonlinearity. There are different ways to construct ROM, whether physics or data based approaches. Among which, the ANSYS ROM procedure provides an extremely versatile and scalable modelling solution to represent the numerical substructure. ANSYS offers powerful modelling capability and rich element library for a wide variety of industries. The execution time of ROM on the target PC is highly predictable and efficient. Thus makes it an attractive option for certain type of real-time hybrid simulation applications.

### **Fatigue coupled with hybrid simulation solution**

Specimens like wind turbine blades could have very long service life. During this period of time, the material properties could change significantly. There are many factors that can cause specimen aging. Among them are corrosion, mechanical loading, delamination, joint loosening, and oxidization. Some elastomer isolation components, for example, can see up to 30% of loading change under same working environment during the service life due to material aging induced property change. It is important to consider specimen aging during fatigue tests. Hybrid simulation is an idea tool to consider the aging effect since the model can be updated during the fatigue test to reflect the impact of the loading environment.

To consider the aging effect, fatigue testing should be divided to multiple sections. A hybrid simulation should be conducted before each section of fatigue test to provide the loading time history commands. The analysis model needs to be updated to reflect the property change of the materials due to the aging effect at different stages of the service life. Figure 3 shows the flow of hybrid simulation coupled with fatigue test.

### **Test control**

To test large scale specimens, such as wind turbine blades, large motion and high forces usually are needed. As a result, nonlinear geometric transformation between actuator coordinate systems and global coordinate system needs to be conducted. The loading configurations are often in over-constrained situations meaning that there are more actuators than the number of degrees of freedom they are controlling. MTS Degrees-of-Freedom (DOF) control software is an idea tool for this kind of applications. It can control any degrees of freedom in global coordinate system with fast and accurate solving. The DOF control software is able to control motion, force, or acceleration of any point in global coordinate system with any number of actuators. It can also provide mixed control mode

(For example, vertical in force control, lateral in displacement control), as well as handling over constrained and cross coupled loading conditions.

Due to these advantages, more and more researchers use MTS DOF control software to conduct hybrid simulation. This control software will be used for the upcoming hybrid simulation and fatigue testing for the full scale turbine blade.

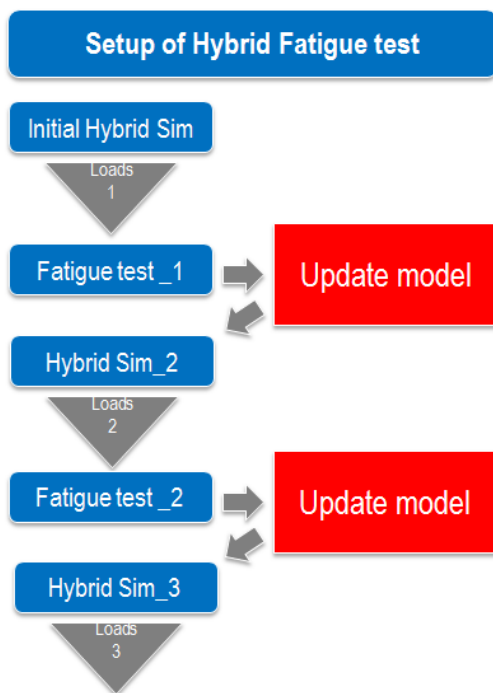


Figure 3, flow of hybrid simulation coupled with fatigue test

### Test verification

To verify the approaches of hybrid simulation using ANSYS as well as hybrid simulation coupled with fatigue test, a simple test configuration was setup as shown in Figure 4. The numerical substructure was a 3-D one-bay, one-level frame structure with seven regular beam elements and one generic client element for communicating with OpenFresco. Ten seconds of El Centro earthquake was simulated with 500 simulation steps. The hybrid simulation tasks were carried out successfully. Table 1 shows the execution times for two cases of hybrid simulation. In the first case, 0.05 seconds was allowed for actuators to execute each set of command after each simulation step. In the second case, no time was allowed for actuators to follow commands.

These test cases demonstrated that even for an extremely simple ANSYS model like shown in Figure 4, the hybrid simulation could not be done in real-time due to CPU time and



communication time. Therefore, ANSYS-OpenFresco approach is only for slow hybrid simulation. To achieve real-time effect, ROM approach was also conducted. Even with much more complicated ANSYS model, real-time hybrid simulation was easily accomplished.

The ANSYS model was created such that, during solving, it wrote the displacement or force commands to a specific file in MTS Profile Command format so that the file could be directly read in as a command file by MTS test control software and conduct subsequent fatigue test. With proper tuning and specimen protection device, the hybrid simulation coupled with fatigue test was successfully carried out.



Figure 4, A hybrid test system with one column being tested

Step Ramp Time (S)	Total CPU Time (S)	Total Ramp Time (S)	Elapse Time (S)	Communication Time (S)
0.05	10.5	25	42	6.5
0	10.3	0	17	6.7

Table 1: Hybrid simulation task execution time

### Conclusions

A hybrid simulation process of wind turbine blades has been outlined. A user defined generic client element was created in ANSYS to establish the connection between ANSYS and OpenFresco so that ANSYS can be used in hybrid simulation. To consider specimen aging during the service life, a hybrid simulation coupled with fatigue testing process was created where ANSYS outputs command files in MTS Profile Command format for the subsequent fatigue test. This process was validated by a small scale test conducted at MTS. A full scale wind turbine blade hybrid simulation coupled with fatigue test will be conducted at DTU in the near future.



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